THE HOWARD H.
BAKER JR
CENTER
for PUBLIC POLICY

WHITE PAPER

Deep Decarbonization and Deep Uncertainty: What are Climate Action Plans Missing?

David L. Greene
Research Professor
Howard H. Baker, Jr. Center for Public Policy
Department of Civil and Environmental Engineering
The University of Tennessee

January 12, 2021

THE UNIVERSITY OF
TENNESSEE
KNOXVILLE

THE HOWARD H. BAKER JR CENTER for PUBLIC POLICY

Baker Center Board (Active Members)

Dr. Michael Adams
President Emeritus, University of Georgia

Cynthia Baker
Former Vice President, Tribune Broadcasting

Darek Baker

Patrick Butler
President and CEO, America's Public Television Stations

Dr. Jimmy G. Cheek
Chancellor Emeritus, The University of Tennessee, Knoxville

Dr. Wayne Davis
Interim Chancellor, University of Tennessee, Knoxville

David Golden
Senior Vice President, Eastman

Thomas Griscom
Former Executive Editor and Publisher, *Chattanooga Times Free Press* and Former Director of Communications, President Reagan

Beth Harwell
Former Speaker of the Tennessee State House of Representatives, Member, Board of Directors, Tennessee Valley Authority

James Haslam II
Founder, Pilot Corporation and The University of Tennessee Board of Trustees

Dr. Theresa Lee
Dean, College of Arts and Sciences, University of Tennessee, Knoxville

Margaret Scobey
Former Ambassador to Syria and Egypt

Don C. Stansberry Jr.
Attorney (retired), Baker, Worthington, Crossley and Stansberry

The Honorable Don Sundquist
Former Governor of Tennessee

John Tolsma
Founder, Knowledge Launch

Lindsay Twardy
Chief of Staff, Oak Ridge National Laboratory

Dr. Thomas Zacharia
Director, Oak Ridge National Laboratory

Baker Center Board (Emeritus Members)

Sarah Keeton Campbell
Attorney, Special Assistant to the Solicitor General and the Attorney General

AB Culvahouse Jr.
Attorney and Partner, O'Melveny & Myers, LLP

The Honorable Albert Gore Jr.
Former Vice President of The United States
Former United States Senator

Joseph E. Johnson
Former President, University of Tennessee

William Johnson
President and CEO, Tennessee Valley Authority

Fred Marcum
Former Senior Advisor to Senator Baker

Amb. George Cranwell Montgomery
Former Ambassador to the Sultanate of Oman

Regina Murray, Knoxville, TN

Lee Riedinger
Vice Chancellor, The University of Tennessee, Knoxville

Robert Waller
Former President and CEO, Mayo Clinic

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Baker Center Staff

Matt Murray, PhD
Director

Katie Cahill, PhD
Associate Director

Jon Ring, PhD
Director of Student Programs

Charles Sims, PhD
Faculty Fellow

Krista Wiegand, PhD
Faculty Fellow

Jilleah Welch, PhD
Research Associate

Elizabeth Woody
Events Coordinator

Darcy Coffy
Administrative Specialist

About the Baker Center
The Howard H. Baker Jr. Center for Public Policy is an education and research center that serves the University of Tennessee, Knoxville, and the public. The Baker Center is a nonpartisan institute devoted to education and public policy scholarship focused on energy and the environment, global security, and leadership and governance.

Howard H. Baker Jr. Center for Public Policy
1640 Cumberland Avenue
Knoxville, TN 37996-3340

Additional publications available at
http://bakercenter.utk.edu/publications/

Disclaimer
Findings and opinions conveyed herein are those of the authors only and do not necessarily represent an official position of the Howard H. Baker Jr. Center for Public Policy or the University of Tennessee.

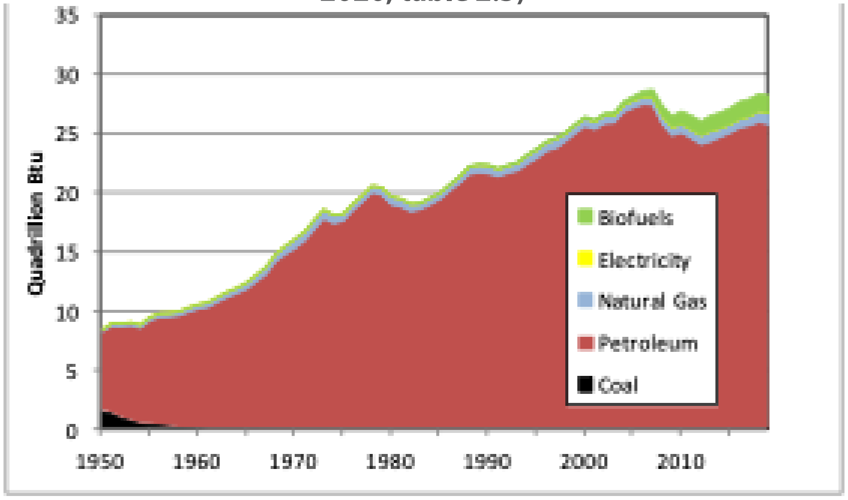
Deep Decarbonization and Deep Uncertainty: What are Climate Action Plans Missing?

David L. Greene[1]

Introduction

Achieving near zero greenhouse gas emissions from transportation by 2050 presents a unique challenge for public policy. Nothing can be moved without energy and today transportation relies on fossil carbon fuels for more than 90% of its energy requirements, as it has done since at least the middle of the last century (Figure 1) (Davis et al., 2020; EIA, 2020). To achieve a level of decarbonization necessary to prevent the most dangerous climate changes, a comprehensive transformation of transportation's energy sources, carriers and uses must be urgently accomplished (IPCC, 2018; NRC, 2020). Moreover, transportation's energy transition must be achieved in concert with a global energy system transition. For example, if all-electric or hydrogen fuel cell vehicles are to realize their full mitigation potential, the entire upstream processes that produce these energy carriers and the materials as well as the processes used to produce vehicles and supporting infrastructure must be decarbonized over their full lifecycles.

Figure 1. Transportation Energy Use by Fuel: 1950-2019 (EIA, 2020, table 2.5)



Three decades is a relatively long time frame for public policy and yet it is a short time relative to the time constants for change in transportation and the energy system. It can take a decade or more from the initiation of research and development to the introduction of a commercial product (White House, 2016, Fig. 4-3). Replacing the existing stock of transportation vehicles takes even longer. Half or more of the passenger cars and light trucks sold in the United States today will still be on the road after 2035 (EPA, 2016) and survival rates and expected longevity have been increasing for decades (e.g., Bento et al., 2018). Medium and heavy duty road vehicle lifetimes are longer still and have also been increasing (Davis et al., 2020, tables 3.13 and 3.14). Half of the commercial airliners sold today are likely to be in use 20 to 30 years later (Jiang, 2013). Before the on-road stock of transportation vehicles is replaced,

---

[1] The author gratefully acknowledges the support of the Clean Air Task Force for researching and writing this paper. The author thanks Dr. Matteo Muratori (National Renewable Energy Laboratory), Dr. Charles Sims (University of Tennessee) and Dr. David McCollum (EPRI) for their critical reviews, comments and suggestions for improving an earlier version of this paper. The views expressed herein are those of the author alone and not necessarily those of the reviewers, the Clean Air Task Force, the National Renewable Energy Laboratory, the University of Tennessee or EPRI.

new vehicle offerings must be converted to zero or near-zero emission technologies. Of the 2,522 makes, models, engine and transmission configurations of 2020 model year light-duty vehicles available to U.S. consumers, 73 (2.9%) are battery electric vehicles, 86 (3.4%) are plug-in electrics and only 8 (0.3%) are hydrogen fuel cell vehicles (www.fueleconomy.gov, 2020). Shares of sales are smaller: BEV 1.4%, PHEV 0.5%, FCEV 0.01% at the national level but four times higher in California (AFDC, 2020b; CAFCP, 2020, FRED, 2020a. If vehicle manufacturers decided tomorrow to convert all their vehicles to battery electric (BEV) or fuel cell electric vehicles (FCEV)s as quickly as possible, it would take at least five years and undoubtedly longer before all makes and models were available as ZEVs (NAS, 2013). In addition, there is the unknown amount of time it will take for novel vehicle technology to be widely adopted by consumers and firms. Even with an all-out effort, reducing transportation's GHG emissions to net zero, or even by 80%, by 2050 will be very difficult.

Deep decarbonization (DD) of transportation will require a comprehensive transformation of a wide-ranging socio-techno-economic system that affects nearly every aspect of society. Not only technology and infrastructure must change but institutions and behavior must adapt. There are numerous, substantial barriers to change but there are also strong positive feedbacks: learning-by-doing, scale economies, network effects in infrastructure and institutions, and overcoming consumers' aversion to the risk of novel technologies. Such positive feedbacks create tipping points that can turn an uphill battle into a downhill run.

A view widely held by environmental economists is that because GHG emissions are an externality the optimal solution is to price the damage they will do via a tax on carbon (Economists, 2019).[2] A more complete understanding of what a large-scale transformation of the global energy system involves has led to the realization that it is not a simple matter of internalizing an external cost and cannot be solved simply by pricing carbon.[3]

> "First, carbon pricing frames climate change as a market failure rather than as a fundamental system problem. Second, it places particular weight on efficiency as opposed to effectiveness. Third, it tends to stimulate the optimization of existing systems rather than transformation. Fourth, it suggests a universal instead of context-sensitive policy approach. Fifth, it fails to reflect political realities."
>
> "In order to address the urgency of climate change and to achieve deep decarbonization, climate policy responses need to move beyond market failure reasoning and focus on fundamental changes in existing socio-technical systems such as energy, mobility, food and industrial production."
>
> Instead, carbon pricing should be used as a part of a policy mix that promotes innovation and decline, accounts for political dynamics, varies between sectors

---

[2] Many economists recognize additional market failure that hinder solving the problem by pricing alone. Borenstein (2019) points to the difficulty of capturing the full benefits of innovation while others find a tendency of markets to under-invest in energy efficiency (e.g., Gillingham and Palmer, 2014; Gerarden et al,., 2015).

[3] The fact that the general solution to the problem of external costs requires consideration of systemic effects was recognized more than half a century ago by another renowned economist: "It almost goes without saying that this problem has to be looked at in total and at the margin." "In devising and choosing between social arrangements we should have regard for the total effect. This, above all, is the change in approach which I am advocating."(Coase, 1960, "The Problem of Social Cost", J. Law & Economics, 3:2-44)

> and over time, and aims at profound system change." (Rosenbloom et al, 2020, PNAS, 117(16): 8664-8668)

Accomplishing a large-scale energy transition for the public good is not only a complex and systemic challenge it is also replete with uncertainties. The process requires decades, making it inevitable that there will be unpredictable technological, economic, political and social changes. How consumers and firms will respond to zero emission vehicles and fuels is not well understood. Nor is it clear what policies voters and their representatives will find acceptable over the next 30 years. How the global economy will change in response to a low carbon energy system is also likely to contain surprises. Even knowledge of the timing, nature, geographical distribution and intensity of the consequences of different levels of GHG emissions is still evolving. Decision science has a special term for this kind of uncertainty.

> "A multi-decade evolution of technologies, socio-economic conditions and politics, such as that associated with a transition to a net-zero energy system, is characterized by deep uncertainty." (Waisman et al., 2019, p. 263. Emphasis added.)

Among the many unprecedented challenges accomplishing a large-scale energy transition for the public good poses for public policy, the need to cope with deep uncertainty is one of the most difficult.

Challenges of Deep Uncertainty for Deep Decarbonization

Deep uncertainty is defined as a situation in which experts and decision makers cannot agree on the probabilities of relevant influencing factors[4], the appropriate models for representing the phenomenon, and perhaps even how to value the possible outcomes (Lempert et al., 2003; Marchau et al., 2019). Anticipating and analyzing both known and out-of the ordinary extreme events is a difficult but not unsolvable problem for modelers and decision makers (McCollum et al., 2020). Methods developed for planning and policy making under deep uncertainty are summarized in Section IV. This section describes the kinds of uncertainties likely to have a major influence on the transition to low-carbon energy. The unknowns are numerous, pervasive and will strongly influence the success of DD policies. For the purpose of discussion, the many varied uncertainties are grouped into four categories: 1) Future technology, 2) Behavioral, 3) Policy support and, 4) Global market uncertainty (Table 1). The following section illustrates each category by discussing a specific uncertainty.

Technological Uncertainty

Uncertainty about the rate and direction of technological progress affects the cost and feasibility of deeply decarbonizing transportation. The zero emission technologies necessary to achieve net zero transportation's GHG emissions are not yet compelling from the perspectives of consumers' and businesses' self-interest. For example, the cost of batteries today makes BEVs more expensive to purchase than conventional vehicles. Although steadily improving, limited range, long recharging times an inadequate fast charging network and lack of home base charging for many househols remain drawbacks for BEVs. Hydrogen fuel cell vehicles are also more expensive, their refueling network in the U.S. is essentially

---

[4] Knight (1921) distinguishes decision making under "risk" where probabilities are known from "true uncertainty" where they are not.

nonexistent, with only 44 stations in operation in California, and the cost of hydrogen at the pump is currently too high to be competitive. In addition, the GHG mitigation benefits of EVs and FCEVs depend critically on decarbonizing fuel and vehicle supply chains. The viability of options for heavy vehicles, aircraft, trains and ships are even less clear. Technological change is moving rapidly in the right direction yet the eventual outcome remains uncertain. Over the coming decades there will be economic, social and political changes that may promote or hinder progress toward DD. Complementary to uncertainty about low carbon technologies is uncertainty about future improvements to conventional fossil-fuel based technologies that could make it more difficult to displace them.[5]

Behavioral Uncertainty

Individuals' behavioral responses, especially the rates of adoption of zero emission and energy efficient vehicles will determine how quickly and completely DD can be achieved. While it has long been known that the great majority of consumers are wary of innovations (Rogers, 1995), there is no way to reliably predict how quickly markets will adopt any particular technology. Despite decades of experience with fuel economy and emission regulations, how real (as opposed to theoretical) consumers make decisions about energy efficient technology and its full effect on energy use and GHG emissions remains unresolved (e.g., Greene, 2019). While it is clear that public charging infrastructure adds value to plug-in vehicles (Greene et al., 2020d), it is not clear to what extent a ubiquitous charging network would offset the BEV's perceived disadvantages of limited ranges and longer charging times and consequently market acceptance of BEVs. Accelerating the adoption of zero emission vehicles is essential to urgently achieving DD.

Uncertainty about Public Support for Deep Decarbonization

> "In the end, all this has to fit into a political process, which has always been a real source of 'deep uncertainty'." (Haasnoot et al., 2013, p. 496)

Public support for DD policies is essential but can be undermined by lack of knowledge, misinformation, disinformation, the public's perceptions of the fairness of particular policies and of the urgency of GHG mitigation, and inequitable distribution of the costs and benefits of DD. The lack of commitment to DD in the United States, in particular, is largely due to inadequate public support. Although a majority of Americans believe the government should do more to mitigate climate change, only about half of the public believes that human activity contributes to climate change "a great deal", and the issue has been made politically divisive (PRC, 2020) by deliberate dissemination of misinformation and false attacks on the trustworthiness of scientific and governmental institutions (e.g., Treen et al., 2020). Regions and communities that are dependent on the extraction and processing of fossil fuels will suffer serious economic decline unless actions are taken proactively to successfully transition workers and business into the new economy (e.g., Just Transition Fund, 2020; EC, 2020). The regressive effect of pricing carbon can be substantially offset by returning the revenues collected to low and middle income individuals (e.g., Stone, 2015), and the periodic receipt of such carbon dividends would likely contribute to public support (CLC, 2020). The energy

---

[5] Although carbon capture from transportation vehicles is not presently economically feasible, it is technically feasible and its potential future use, especially in heavy-duty vehicles, ships or railroads cannot be dismissed (e.g., Reynolds, 2019; Sharma and Marechal, 2019).

industry is part of the public, and its concerns about investing in DD tend to be driven by uncertainty about whether and when such investments will be profitable. As low-carbon vehicles and energy carriers replace fossil-fueled internal combustion vehicles, it is also unclear how the public will react to the decreasing availability of gasoline and the obsolescence of the ICE vehicles they own.

Global Market Uncertainties

At the global scale, DD efforts will be affected by markets and geopolitics. Global supply chains and resource demands will change in profound ways. For example, DD will undoubtedly cause the prices of fossil fuels to decrease making low carbon alternatives appear more expensive. In the absence of policies that create value in reducing fossil fuel use, firms in the energy industry will consider investments in low and zero carbon energy sources to be risky (e.g., bp, 2020; CLC, 2020). Increased demand for new resources such as rare earths for electric motors or lithium, cobalt and other minerals for batteries could increase their prices (Griem et al, 2020), hindering market acceptance. Maintaining and strengthening the international consensus on DD will also be a challenge.

Examples of the Four Types of Uncertainty

To make the four categories of uncertainty more concrete, four specific examples are described in this section. Technological uncertainty is illustrated by the uncertain future costs of Battery Electric Vehicles (BEV) and hydrogen Fuel Cell Electric Vehicles (FCEV) and the question of whether to focus limited resources on deployment of only one or both. Market uncertainty is illustrated by the surprisingly low market acceptance of hybrid electric vehicles (HEV) and the factors that influence their uptake. Political uncertainty is illustrated by analyzing reasons for the popularity and durability of fuel economy and GHG emission standards and lessons learned about what makes pubic policies durable. Finally, uncertainty

Table 1. A Typology of Uncertainties Affecting Public Policy to Deeply Decarbonize Tennessee

Future Attributes of Low Carbon and Competing Technologies
- Cost and energy density of batteries
- Carbon intensity and cost of electricity
- Adequacy and cost of recharging infrastructure
- Cost and performance of fuel cells
- Cost and carbon intensity of dispensed hydrogen
- Cost and carbon intensity of liquid fuels
- Rates of learning by doing
- Extent of scale economies
- Technological advances in the internal combustion engine (ICE) vehicles
- Effects of automated vehicle technology

Market Response to Low-Carbon Technologies
- How the market for energy efficiency works (experts don't agree)
- Nature and intensity of consumer resistance to zero emission vehicles
- Willingness of the public to change behaviors, e.g. share vehicles and rides
- Time required to overcome resistance to novel technology
- Value of charging/refueling infrastructure and effect on vehicle choice
- Impacts of ZEVs on public revenue sources (e.g., motor fuel tax)
- Industry uncertainty about the future viability of ZEVs and low-C fuels

Political Acceptance of Decarbonization Policies
- Public acceptance of need to urgently mitigate climate change
- Depth and continuity of public support of vehicle efficiency/ghg regulation
- Difficulty envisioning what would have happened without strong climate policies
- Extent and effectiveness of misinformation and disinformation
- Extent and effectiveness of ideological opposition to popular policies (real vs. ideal markets)
- Public support for carbon tax/cap and trade
- Public support for ZEV subsidies
- Public support for charging/refueling infrastructure deployment
- Resistance to the decline of ICE vehicles and gasoline availability

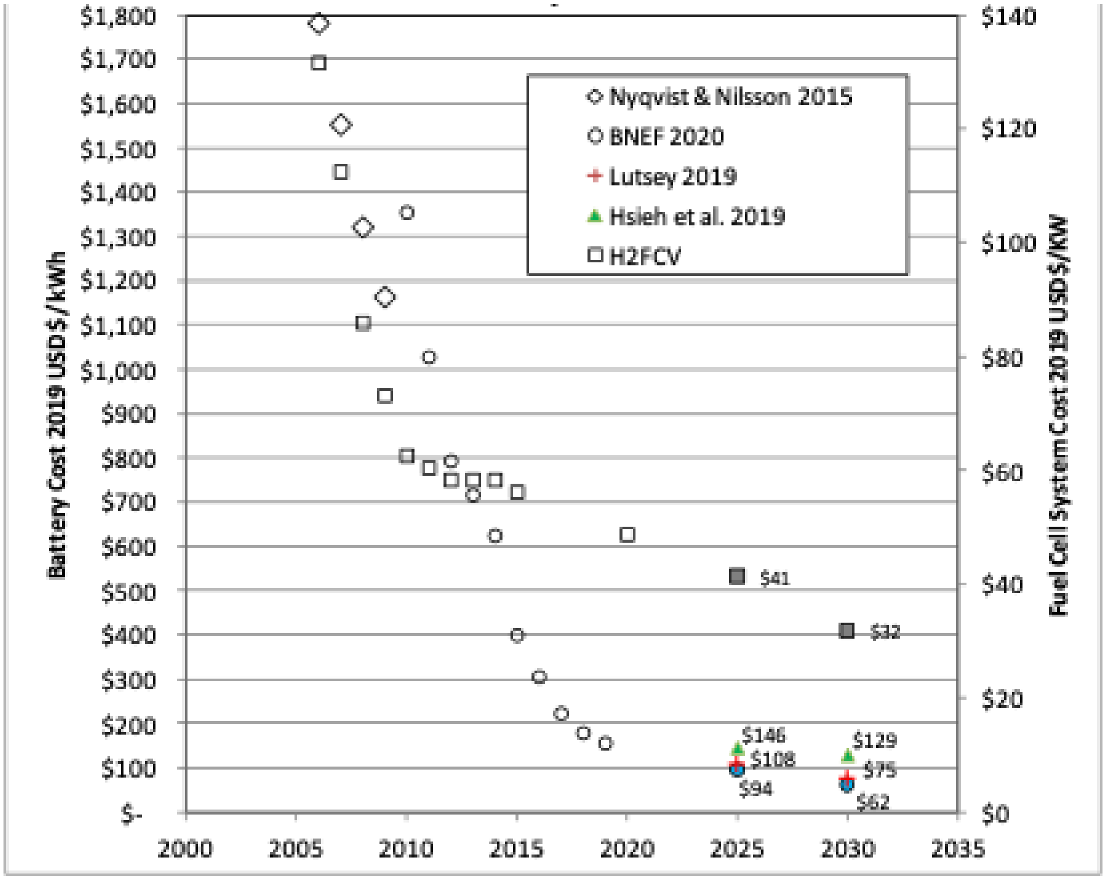
Global Responses to the Transition to a Low Carbon Energy System
- Effect of global decarbonization on the price of fossil energy sources (especially oil)
- Supply and cost of important natural resources (e.g., rare earths)
- Durability and effectiveness of international consensus and cooperation

Unknown unknowns

about the global response to DD is illustrated by considering the possible impacts on the price of fossil carbon, specifically petroleum.

Technological uncertainty: BEVs or FCEV: Which technology will succeed?

Figure 2. Estimates and projections of lithium-ion battery and hydrogen fuel cell system costs.



(Fuel cell costs are shown as squares. Historical costs are open symbols, projections as solid colors.)

For technologies that require substantial, long-lived capital investments, having the flexibility of multiple options is important to mitigating the risk of uncertainties like future technological progress and fossil fuel prices (Usher and Strachan, 2012). The two leading ZEV technologies, battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) have made impressive progress over the past two decades. The cost of batteries, the key determinant of the BEV's cost competitiveness, has decreased by two orders of magnitude over the past decade alone (Figure 2). Meanwhile FCEVs have gone from experimental prototypes to commercial products. Over the past decade, the cost of automotive fuel cell systems has been reduced by a factor of three. Unfortunately, past performance does not necessarily guarantee future success.

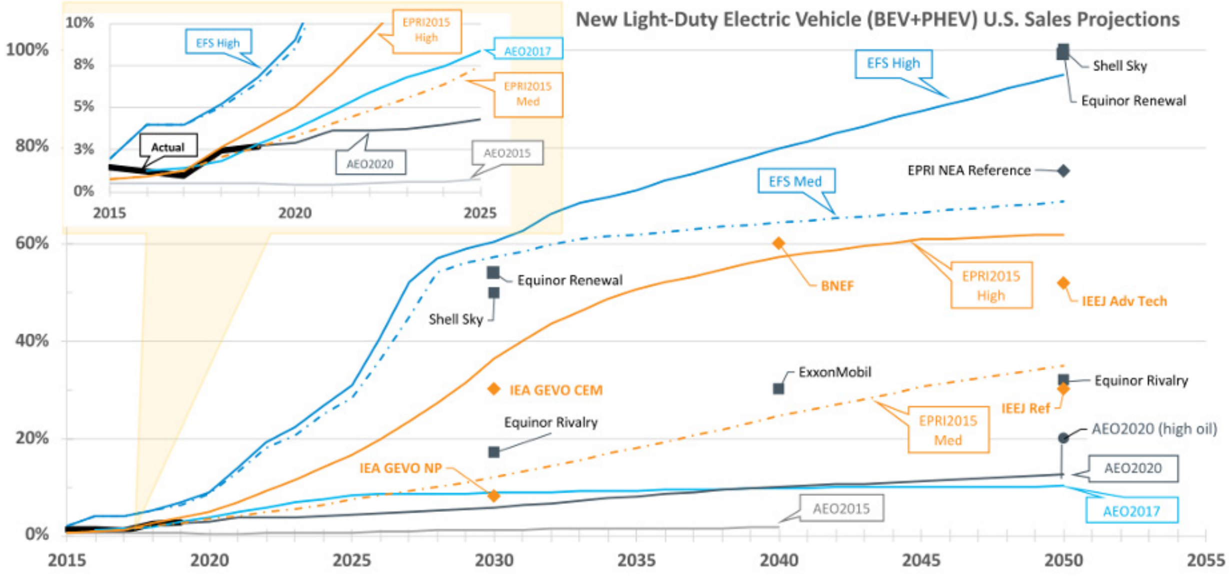
The two technologies differ in ways that may make them complements as well as competitors. BEVs have a clear first mover advantage: 300,000 BEVs were sold in the U.S.

in 2019 but only 2,089 FCEVs (AFDC, 2020b; CAFCP, 2020). BEVs have the backbone of a ubiquitous energy infrastructure in the electricity grid, plus 26,784 public charging stations already in place (AFDC, 2020c).[6] FCEVs have the advantage of rapid refueling, equivalent to that of a conventional gasoline vehicle. Both energy carriers have far lower energy densities than gasoline or diesel fuel but hydrogen's higher energy density relative to electricity and fast refueling may give it an advantage in the medium- and heavy-duty vehicle markets.

However, both technologies require further improvement to be equal or better than conventional internal combustion engine (ICE) vehicles in terms of private costs and benefits to car buyers. At present, sales of both technologies are heavily dependent on public policy, particularly ZEV mandates and subsidies in the form of tax credits or rebates to car buyers. Both benefit from public policies supporting the deployment of recharging/refueling infrastructure but for FCEVs early deployment of refueling stations is essential to enabling any meaningful market share.

Supporting both ZEV technologies costs more than supporting only one and, to a certain degree, the two will also compete for market share. Should public policy pick a winner and focus on its success or hedge its bets by continuing to support both? The question could be easily answered if there were no uncertainty about future technological progress and future market success. In fact, both are uncertain. Projections of the market share of BEVs through 2050, for example, range from about 10% to almost 100% (Figure 3). And while cost curves can be fitted to the data in Figure 2 and extrapolated, in reality technological progress is not so easily predicted.

Figure 3. Projections of the Market Share of Plug-in Electric Vehicles (Fig. 1 in Muratori et al., 2020)



Plug-in electric vehicles are in the market and sales are growing. Total U.S. sales through 2019 amount to almost 1.5 million vehicles on the road with over 325,000 sold in 2019 (AFDC, 2020b). Worldwide PEV sales exceeded 2.1 million in 2019, bringing the global

---

[6] This count includes pubic Level 2 and DC fast charging stations, whether available to all BEVs or only to Teslas.

stock of PEVs to 7.2 million vehicles (IEA, 2020). In the U.S., public charging infrastructure now comprises almost 25,000 level 2 chargers and almost 4,000 fast chargers (DCFC) (AFDC, 2020c). Globally, there are approximately 800,000 public chargers (IEA, 2020). In terms of market development, hydrogen fuel cell vehicles are far behind. In the U.S. total FCEV sales amount to only 8,573 vehicles supported by 44 stations, all but one of which is in California (CAFCP, 2020). Several nations have ambitious plans for FCEVs and are actively deploying stations. At the end of 2019 there were 114 hydrogen refueling stations in the EU, 110 in Japan, 37 in South Korea and 28 in China (Greene et al., 2020).

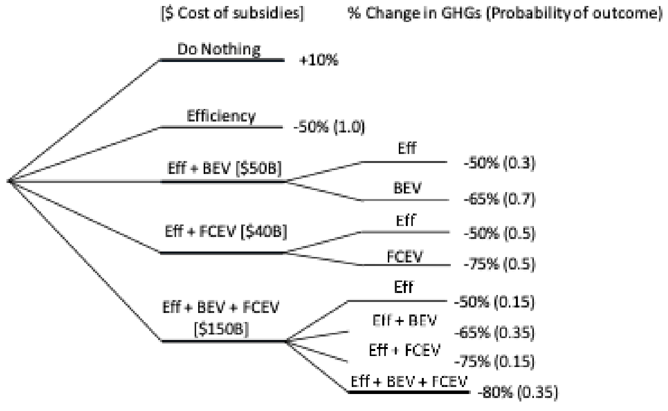
What's the best policy decision: continue supporting both BEVs and FCEVs, abandon FCEVs and put all the effort into BEVs, abandon BEVs and focus on FCEVs or give up on both technologies? The choice is difficult because of uncertainty about the technological progress of the two technologies and their adoption by consumers. Engineering Options Analysis (EOA, described in Section IV) offers one way to cope with the uncertainty. It is also the most straightforward of the five methods described and lends itself to a simplified illustrative example.

Figure 4 depicts the decision tree. It is based on modeling by the National Research Council (NRC, 2013) but greatly simplified with rounded and somewhat altered the numbers. Acknowledging the many uncertainties in their modeling, the NRC Committee offered the following caution:

> "The modeling analysis presented in this chapter is intended to be an initial step in the right direction rather than a definitive assessment of future alternatives. The models...are first generation efforts, more useful for understanding processes and their interactions than producing definitive results." (NRC, 2013, p. 129)

Indeed, some of the NRC study's key assumptions have already proven to be incorrect. For example, the Committee assumed that battery costs would fall to $250/kWh by 2030 and $160 by 2050, a level that appears to have been achieved in 2019 (see Figure 2). Their Reference Case also assumed that aggressive improvement to energy efficiency supported by two strong pricing policies would continue throughout the period.[7] The combination of efficiency standards and pricing policies alone was estimated to reduce light-duty vehicle GHG emissions by 50% in 2050 (Figure 4). The NRC (2013) estimates are used here to provide the numbers for a simple

Figure 4. Example Engineering Options Analysis Decision Tree for BEV and FCEV Policies



---

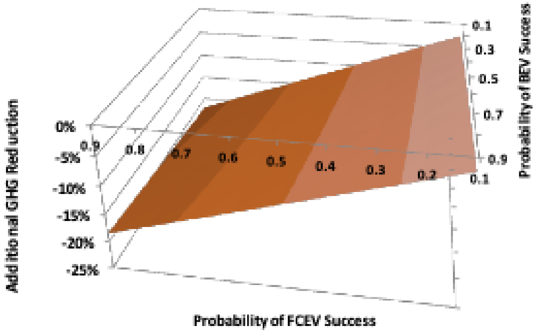
[7] The NRC (2013) "Efficiency" case includes two supporting pricing policies: 1) an increasing highway user fee in the form of an energy tax indexed to the average energy efficiency of all vehicles, that increases from $0.42/gal. in 2010 to $1.27/gal. in 2050 (e.g., see Greene, 2011), 2) a system of feebates, a revenue neutral system of subsidies for efficient vehicles and taxes on inefficient vehicles that reflects the social cost of ghg emissions.

illustration of EOA, and also to show how deep uncertainty means that many of one's initial assumptions will turn out to be incorrect.

The costs of subsidies [in square brackets] and estimated payoffs in emissions reductions relative to 2005 levels are rounded numbers from the NRC (2013) report. The probabilities of success (i.e., achieving reductions at the cost shown) are not available in the NRC report and were added for the purpose of illustrating the method. All of the ZEV cases assume continued efficiency improvements and pricing policies, and so costs and benefits are incremental to the NRC's Efficiency case. If nothing is done, GHG emissions are estimated to increase by 10% over 2005 levels by 2050. Aggressive efficiency improvement plus other policies that raise fuel costs produce a 50% reduction in 2050. If BEVs alone are successful (assigned a probability of 0.7), the reduction increases to 65%.[8] If BEVs are not successful, the default is the Efficiency case, an eventuality that has a probability of 1-0.7 = 0.3. Adding only FCEVs using low-carbon hydrogen to the Efficiency Case achieves a 75% reduction, but FCEVs' probability of success is set at only 0.5. The probabilities in the lowest branch of the decision tree are calculated assuming the probabilities of BEV and FCEV success are independent.[9]

If the criterion for choosing an option is the expected reduction in GHG emissions by 2050, continuing to pursue both BEVs and FCEVs in addition to energy efficiency, is the best choice. BEV+FCEV has an expected reduction of 71%.[10] The expectations for BEVs and FCEVs are similar, 61% and 63%, respectively. On the other hand, the BEV+FCEV option costs more than twice as much as either option alone. Is it worth it? Based on the Committee's estimates of total social benefits and costs the answer is, yes. The expected Benefit/Cost ratio of choosing BEV+FCEV over BEV alone is 6.3 and the marginal B/C ratio considering only the value of the additional GHG reductions is still 4.7. So this simplified example points to pursuing both options, despite the greater cost.

Figure 5. Expected Additional GHG Reductions of BEV+FCEV Strategy vs. BEV Only Strategy



The sensitivity of the additional GHG reductions of the BEV+FCEV strategy to the two technologies' probabilities of success can be analyzed by means of "what if" analysis. Outcomes corresponding to probabilities from 0.1 (10%) to 0.9 (90%) are illustrated in Figure 5. Keeping in mind that the analysis is intended only to illustrate decision making under uncertainty, the "what if" analysis indicates that the expected reduction increases over the full

---

[8] This reduction may seem small. It is strongly dependent on the Committee's assumptions about how rapidly electricity generation would be decarbonized.

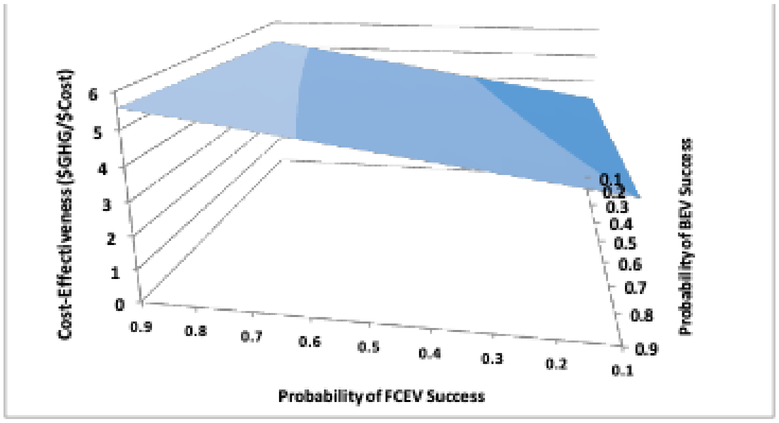
[9] Both technologies share two important technologies: 1) batteries and 2) electric motors and their control systems. However, the critical technologies for FCEVs are the costs of the fuel cell system, on-board storage tank and delivered low-C hydrogen. Assuming independent probabilities of success is therefore not exactly correct but not a reasonable assumption for this simplified example.

[10] The combined impact is from the NAS study. The study's modeling attempts to account for interactions between the two technologies to avoid double counting.

range of probabilities and that the outcome is relatively sensitive to the probability of FCEV success and insensitive to the probability of BEV success (Figure 5).

The effect of the probabilities of success on the cost-effectiveness of the BEV FCEV strategy can also be analyzed. The incremental cost effectiveness of the BEV+FCEV strategy is measured by the ratio of the additional expected value of GHG reductions versus the BEV only strategy, divided by the addition cost (again, rounded numbers taken from NRC 2013). In the example analysis, the incremental cost-effectiveness is not particularly sensitive to the probabilities of success but it is again more sensitive to the probability of FCEV success (Figure 6).

Figure 6. Incremental Cost-Effectiveness of the BEV+FCEV Strategy vs. BEV Only



The BEV+FCEV strategy offers an additional advantage versus the BEV or FCEV only strategies which is the real options value of discontinuing one or the other strategy if probabilities of success change dramatically (e.g., Brandão et al. 2005). In a realistic EOA, a system for monitoring the progress of the technologies would be established to support such a decision. For example, if after a decade of experience, it is learned that the probability of success of FCEVs is very low, say 10%, efforts to promote FCEVs can be discontinued, saving a portion of the $150B cost of the BEV + FCEV pathway. The effect of the option to change the plan based on experience reduces the expected cost of the BEV+FCEV pathway without reducing its expected payoff.

Behavioral Uncertainty: What's holding back consumer acceptance of HEVs?

The central premise of Rogers' seminal innovation diffusion model, first published in 1962, is that social systems have a natural resistance to change. Its key insight is that innovation diffusion is a social process and not simply a rational economic decision made by fully informed, utility maximizing consumers.

> "Diffusion is the process by which an innovation is communicated through certain channels over time among members of a social system." (Rogers, 1995, p.5)

The four elements of diffusion are the innovation, communication channels, time and the social system. Each element has its own uncertainties but since DD is urgent, time and uncertainty about the rate of diffusion are critical. According to Rogers (1995), the rate of diffusion of an innovation depends on five factors:

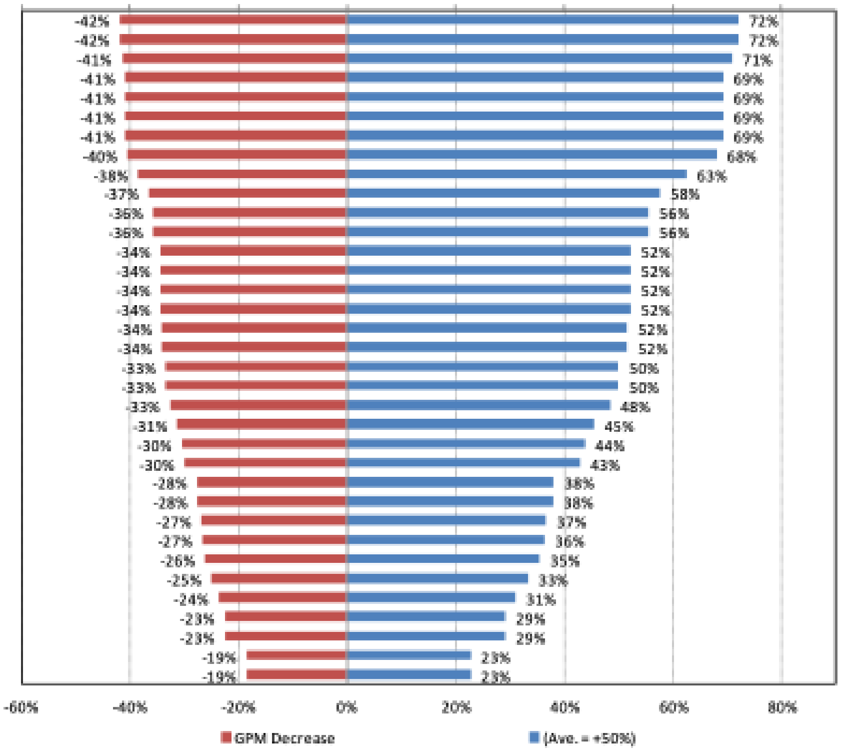
1. Its relative advantage over incumbent technologies
2. Its compatibility with the existing social system
3. Its complexity or understandability
4. Its trialability, i.e., ease with which experience with the technology can be obtained
5. Its observability, i.e., how readily its comparative advantage can be seen.

Table 2. Subjective Rating of Advanced Drivetrain Technologies in 2020, Using Rogers' Five Criteria

Criterion	HEV	PHEV	BEV	FCEV
Relative Advantage	Med	Med	Low	Low
Compatibility	High	High	Med	Low
Complexity	High	High	High	High
Trialability	Low	Low	Low	Low
Observability	Low/Med	Med	Med	Med

Rogers' model for predicting the rate of adoption of a technology is essentially qualitative. There is no proven method for making ex ante quantitative predictions about rates of technology adoption, which produces uncertainty. Using the author's subjective judgment, four relevant vehicle technologies, HEV, PHEV, BEV and FCEV are compared qualitatively, from the private perspective of a car buyer in Table 2. Relative advantage combines price, fuel savings and other attributes. Trialability is low for all options because purchasing, leasing or even

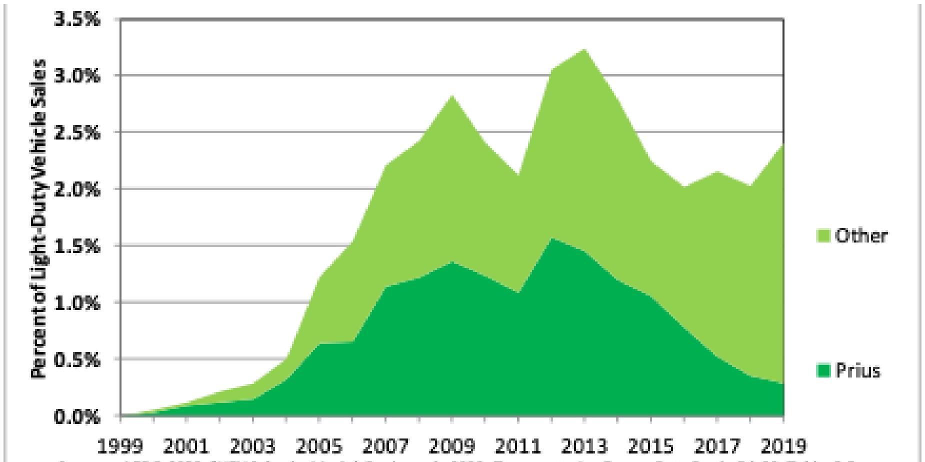
Figure 7. Greenhouse Gas Emission Reduction and Fuel Economy Improvement of Hybrid Electric Vehicles in Comparison to a Conventional Vehicle of the Same Make, Model and Trim.



(www.fueleconomy.gov "Can a Hybrid Save Me Money?")

renting a vehicle for long enough to understand its fuel economy and other relevant attributes is costly.

Figure 8. U.S. Market Share of Light-Duty Hybrid Electric Vehicles.



Sources: AFDC, 2020, "HEV Sales by Model; Davis et al., 2020, Transportation Energy Data Book, Ed. 38, Table 3.5.

According to the author's subjective ratings, the hybrid vehicle does as well or better than the others with the exception of observability. The distinguishing attribute of an HEV is its better fuel economy and although government ratings are readily available, consumers know their MPG will be different (e.g., Greene et al., 2013). Observing the improvement in MPG takes some time and persistence. But HEVs really do get better fuel economy than comparable conventional vehicles; a lot better. The DOE/EPA website fueleconomy.gov has matched all the HEVs that have one with their ICE twin (unfortunately, this leaves out the Prius). For the full set of 35 makes and models, the average improvement in miles per gallon (MPG) of an HEV is 50%, which translates into a 33% reduction in gallons per mile (GPM) and greenhouse gas emissions (Figure 7). Based on MSRP, the average payback period (assuming gasoline at $2.50/gal. and 15,000 miles per year of driving) is 3.5 years (median = 3.2). Hybrids are a bargain. Hybrids have been in the market for two decades, have no disadvantages compared to conventional vehicles, and received government subsidies in their early years (now discontinued). And yet they account for less than 3% of all light-duty vehicle sales (Figure 8).

Why have hybrids not been more successful, especially over the decade from 2005 to 2014 when the price of gasoline frequently exceeded $3/gallon? The novelty of hybrid technology may be one reason. Even though hybrids have been around for two decades, only a minority of consumers in 2013 and 2017 surveys could identify the correct method of refueling an HEV (Long et al., 2019). Information diffusion can be slow, and then there is disinformation. And even though the monetary advantages of hybrids are clear, consumers may not see it that way. There is substantial evidence that the "energy efficiency gap", the tendency for markets to fail to adopt cost-effective energy efficiency technologies, applies to the market for light-duty vehicles (e.g., Gillingham and Palmer, 2014; Gerarden et al., 2015; Greene, 2019).[11]

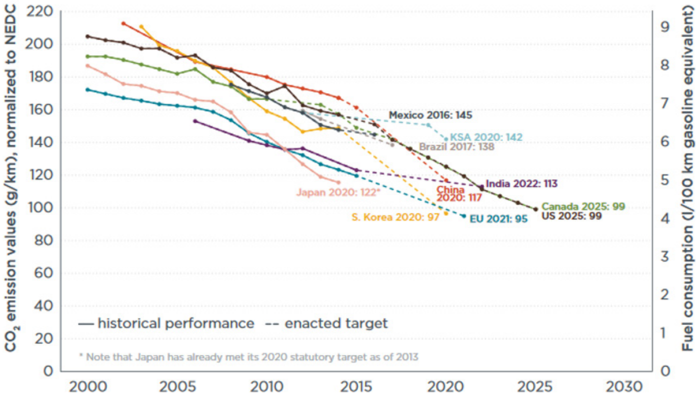
System transformations produce strong positive feedbacks that create tipping points. When will BEVs reach their tipping point? How long will it take for PEVs or FCEVs to capture 50% of the light-duty vehicle market? We don't know. As Figure 3 illustrates, projections for PEVs' market share in 2050 range from about 10% to 100%, a span that, by itself, contains almost no useful information. How long should PEVs be subsidized before we reach the tipping point at which they become competitive without subsidies? That depends on the rate of diffusion, the rate of technological progress in batteries especially and, of course, public policy.

Public Acceptance of DD: What can we learn from the durability of fuel economy standards?

Sustained public support is essential if DD policies are to remain in place and effective for decades. Yet, as we have seen in the U.S. since 2016, a shift in political winds can turn progress into regression. What promotes public acceptance of climate change policies and what can be done to reduce uncertainty about sustained future support?

Drews and van den Bergh (2016) reviewed 49 empirical and experimental studies of public support for climate policies, and summarized their findings with respect to social-psychological factors, perceptions of the design of climate policies and contextual factors. Given the focus of this paper, probably their most important finding was the importance of public perception that good solutions exist and can be implemented.

Figure 9. Historical CO2 Emissions per Kilometer and Future Standards for New Passenger Cars as of 2017, Normalized to the NEDC



(Yang and Bandivadekar, 2017).

> "When it comes to public perception, uncertainty about the solutions to climate change might actually be greater and more problematic than uncertainty about the characteristics of climate change itself." (Drews and van den Bergh, 2016, p. 859)

The literature analyzed indicated that the public is most likely to support policies that are perceived as effective and beneficial, that distribute any costs progressively, that recycle any revenues generated to the general public or to taxpayers, and that incentivize change rather than coerce it.

More recent studies lend support to these conclusions. Incentives such as rebates or tax credits were not only highly supported by owners and non-owners of EVs, but support

---

[11] Systematic differences between actual human decision making and the assumptions of rational economic behavior can explain the undervaluing of energy efficiency under normal market conditions and the success of energy efficiency regulations (see, e.g., Greene, 2019).

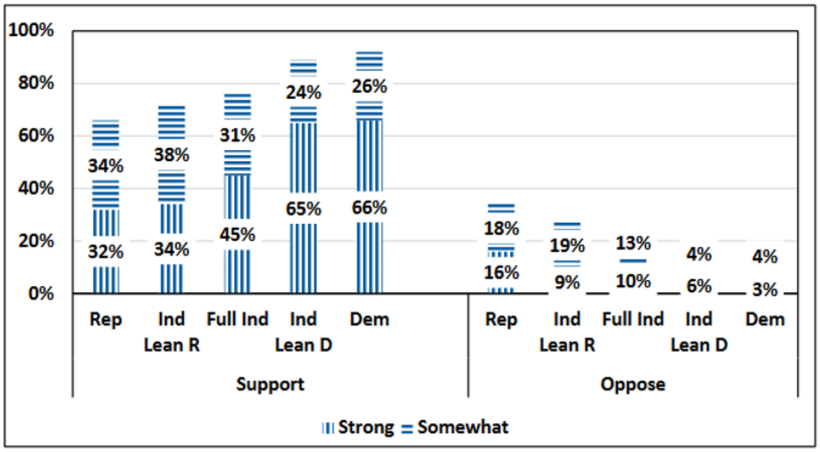
for incentives was not diminished when the cost of subsidies was explained to respondents (Brückmann and Bernauer, 2020). Findings by Huber et al. (2020) echo those of Drews and van den Bergh (2020):

> "Ceteris paribus, the more effective, the less intrusive, and the fairer a policy instrument is perceived to be, the more likely citizens will support it." (Huber et al., 2020, p. 666)

And with respect to perceived fairness, Bergquist et al. (2020) concluded that making economic and social policy objectives an integral part of climate policy increased public support.

Perhaps the most enduring transportation GHG mitigation policy is regulation of vehicle emissions or fuel economy. Ten of the top 15 vehicle markets, accounting for 80% of the world's light-duty vehicle sales, have standards regulating GHG emissions or fuel economy (Yang and Bandivadekar, 2017). Among them are countries with high motor fuel taxes, such as Japan and the nations of the EU. Historical and future standards as of 2017, normalized to the New European Drive Cycle (NEDC) for purposes of comparison are shown in Figure 9.

Figure 10. Public Support for Fuel Economy Standards in 2019 (Gillis and Cooper, 2019)



In the U.S., the Corporate Average Fuel Economy (CAFE) standards, now set jointly with EPA's GHG regulations under the Clean Air Act have been in effect for over 40 years. Public support for the standards, enacted in late 1975 and implemented in 1978 has been strong, broadly based and durable. Seven national random sample surveys conducted between 1988 and 1997 found public approval of the fuel economy standards between 72% and 95% (Greene and Liu, 1998, Table 3; NAS, 2015, Table 9.2). A January 2005 survey found 77% supported raising the standards even though they were told "…it would cost more to buy or lease a car."[12] Support from self-identified Democrats was 83%, Republicans 74%. A 2006 Pew Survey found 86% favored higher standards, the same percentage found by a Mellman survey in 2007. In a 2009 Gallup poll, 82% favored higher standards. The Consumer Federation of America has monitored public sentiment towards the standards since 2009, and found consistent, overwhelming and largely bi-partisan support (Gillis and Cooper, 2019). Overall support has varied between 75% and 85%, with those "strongly" supporting consistently about 50%.

---

[12] For the purpose of measuring public acceptance, surveys that do not state a premise about fuel economy standards before asking respondents whether they approve of the standards should be preferred to surveys that make an assertion about the standards' costs or benefits before asking respondents for their opinions. Prefacing survey questions with statements about the impacts of the standards is likely to bias responses. Questions asked without asserting a premise rely on the respondent's understanding of the effects of the standards.

Even in 2019, 66% of self-identified Republicans supported the standards along with 72% of Republican-leaning independents (Figure 10).

Despite consistent bipartisan public support, from 1985 to 2004 the standards were not increased. In large part this can be attributed to the generally low price of petroleum over most of the period (see Figure 11). On the other hand, it appears to reflect another dimension of political uncertainty, i.e., the fact that public support does not guarantee consistent government action. Acceptance by the regulated industry also matters.

What accounts for the durable popularity of the fuel economy/GHG standards? Although they are a regulatory policy, the fact that the burden falls on the automotive industry and not on the consumer enhances public support (Drews and van den Bergh, 2016). In 2011 their overall economic efficiency was improved by allowing credit trading among manufactures across all makes and models of vehicles. Fairness to manufacturers and perceived fairness to car buyers was addressed by indexing a manufacturer's requirement to the sizes of vehicles it sold. From the consumers' perspective the fuel economy improvements have been cost effective, with fuel cost savings substantially exceeding increased vehicle purchase costs, and they have been accomplished by adopting energy efficient technologies that have been largely invisible to the consumer (Greene et al., 2020a). Finally, because a vehicle's fuel economy is nearly constant over its life but its price depreciates exponentially, the net savings have been progressive, with lower income quintiles saving the most as a percent of income (Greene and Welch, 2018).

Global Response to Deep Decarbonization: A world awash in cheap oil?

When considering DD policies, the scope of uncertainties considered must be expanded to a global scale.

> "A more fulsome treatment of uncertainty is also required, as well as a more in-depth analysis of the linkages between national transformations and global dynamics, notably trade in energy and GHG-intensive materials." (Bataille, et al., 2016, p. S5)

An important advantage of plug-in electric vehicles (PEV) is lower energy cost per mile. But that advantage also depends on the price of gasoline, which depends on the price of crude oil. In July of 2020, with crude oil at about $40 per barrel, the cost of oil accounted for 44% ($0.96) of the $2.18 average cost of a gallon of gasoline (EIA, 2020a). Taxes comprised 22% ($0.48), as did distribution and marketing, while refining made up 11% ($0.24). Decarbonization in transportation and other sectors will reduce global demand for crude oil, putting downward pressure on world oil prices. Lower oil prices, in turn, will mean lower energy costs for internal combustion engine vehicles and that will erode some of the cost advantage of PEVs.

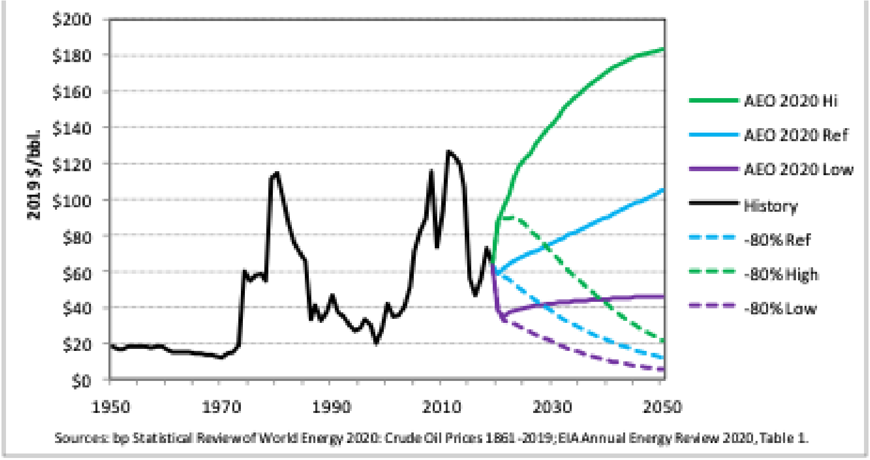
For the past half century, world oil prices have been highly variable (Figure 11) and unpredictable, statistically indistinguishable from a random walk (Hamilton, 2009) .[13] Predictions of future prices through 2050 are therefore highly uncertain, as reflected in

---

[13] Although it is possible to estimate the parameters of a random walk model based on past oil prices, it is also evident that there was a dramatic change in process generating prices after 1970 and no guarantee that another system change would not occur in the future.

the U.S. Energy Information's (USEIA, 2020c) current High, Reference and Low oil price projections. For 2050 the projections span a range from $45 to $185 per barrel (Figure 11). The Reference projection for 2050 is $105 per barrel. Assuming no change in the other cost components, this would make the price of gasoline $3.72 per gallon.

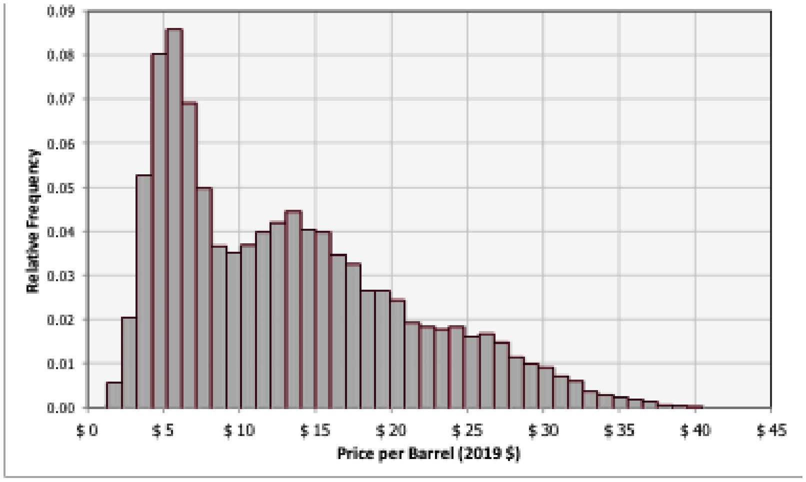
Figure 11. A Century of World Oil Prices and Predictions: 1950-2050 (bp, 2019; USEIA, 2020c).



Sources: bp Statistical Review of World Energy 2020: Crude Oil Prices 1861-2019; EIA Annual Energy Review 2020, Table 1.

Predicting the effect of, say, an 80% reduction in world demand for crude oil is also uncertain. Among other things, it is highly unlikely that estimates of the response of crude oil supply and demand inferred from historical data would apply to such a large reduction in demand. Nonetheless, for the purpose of illustrating the potential reaction of world oil markets it is useful to attempt such a calculation. The calculation begins with the EIA's world oil production projections to 2050 (USEIA, 2020b). Assuming a range of prices elasticities of supply from (+0.2 to +0.5) and demand from (-0.2 to -0.6) with midpoints of +0.35 and -0.4, respectively (Greene et al., 2020b), the effect of an 80% reduction in world oil demand can be calculated. The effect on the Reference oil price projection is to reduce the price of oil in 2050 to just over $12 per barrel, which would imply a pump price for gasoline of about $1.50. Even starting from the High Oil Price case the price of a gallon of gasoline would fall to $1.70, while in the Low Price case a gallon of gas could be had for about $1.35.

Figure 12. Simulated Uncertainty of World Oil Price in 2050 Assuming an 80% Reduction in World Oil Demand, Using AEO High, Low and Reference Oil Price Projections.



Of course, this result is highly uncertain, as illustrated by a Monte Carlo simulation using the elasticity ranges and assuming that the three EIA oil price projections are equally likely (Figure 12). These calculations are intended to be illustrative and not predictions, except of the near certainty that whatever world oil prices would have been in the future, they will be much lower with deep decarbonization of the world's energy system. In the absence of offsetting measures, lower prices for fossil energy will make it more difficult for ZEVs to compete with petroleum fueled ICEs.

In principle, the effect of falling oil prices can be offset by establishing a carbon price that will increase over time or by raising motor fuel taxes. A carbon tax of $100 per ton of CO2 would add about $1 per gallon to the price of gasoline, offsetting about half of a reduction in oil prices from $100 to $12 per barrel. And if motor fuel taxes (as roadway user fees on energy use) were indexed to inflation and also the average energy efficiency of all vehicles on the road, most of the rest could be offset by increased highway user fees for petroleum-powered ICEs, given that the transition to ZEVs will likely increase the average energy efficiency of highway vehicles by well over 100% (Greene, 2011).

Policy and Planning Methods for Coping with Deep Uncertainty

To meet the challenges posed by highly complex systems with long time constants for change, decision science has developed several methods to support rational decision making under deep uncertainty. The key features of five well-established methods are summarized in this section. Despite their different approaches they share several principles in common which will be summarized below.

Robust Decision Making (RDM)

Given deep uncertainty, not only are the probabilities of possible future events unknown but surprises (unknown unknowns) are expected. One of the earliest efforts to rationalize decision making under deep uncertainty focuses on making robust rather than optimal decisions (Lempert et al., 2006). The method begins by constructing a wide variety of possible futures and uses computer modeling to evaluate the performance of different strategies over the full range of future scenarios.

The key elements of Lempert's (2019) Robust Decision Making method are:

1. Considering a multiplicity of plausible futures,
2. Identifying strategies that perform well over a wide range of futures,
3. Choosing strategies that are inherently adaptable and,
4. Using computer modeling interactively with decision makers to facilitate deliberation.

Dynamic Adaptive Planning (DAP)

The Dynamic Adaptive Planning process is comprised of five stages (Walker et al., 2019). In Step I planners and stakeholders define the goals of the project, identify constraints that may limit the scope of action, and analyze a set of actions that might achieve the objectives. In Step II, an initial plan that could achieve the project's goals is constructed and the conditions for success of the plan (vulnerabilities and opportunities) are identified through analysis (e.g., modeling). The purpose of Step III is to improve the robustness of the plan by reducing vulnerabilities and taking advantage of opportunities through five types of anticipatory actions:

a) Mitigating: reduce impacts of certain vulnerabilities
b) Hedging: reduce risks of uncertain vulnerabilities
c) Seizing: take advantage of certain or nearly certain opportunities
d) Exploiting: prepare to take advantage of uncertain opportunities
e) Shaping: act to change the likelihoods of vulnerabilities and opportunities

Step IV in the process establishes a monitoring system to provide the information necessary to know whether the plan is succeeding or not and to alert decision makers to developing vulnerabilities and opportunities. Triggers, indicators of the need to take action are identified. In Step V, planners and stakeholders identify prepare for the actions to be taken in the event triggering events occur.

Dynamic Adaptive Policy Pathways (DAPP)

The Dynamic Adaptive Policy Pathways method is similar to DAP but explicitly addresses the sequencing of decisions over time (pathway) as policies interact with and adapt to the evolution of the system they influence (Haasnoot et al., 2019). The process is comprised of eight steps.

1. Specification of the problem, system, objectives and uncertainties
2. Assessment of vulnerabilities and opportunities
3. Identification of options and reassessment of vulnerabilities and opportunities
4. Design and evaluation of pathways
5. Selection of short- and long-term actions, and design of monitoring system
6. Implementation
7. Monitoring
8. Reassessment and adaptation

The main differences between DAPP and DAP are the greater emphasis on developing alternative pathways, identifying the adaptive tipping points at which the current pathway must be changed, and the lesser emphasis on hedging to reduce uncertainty and shaping to influence uncertainties.

Info-Gap Decision Theory (IGT)

Unlike RMD, DAP and DAPP, Info-Gap Decision Theory is a non-probabilistic approach to decision making under deep uncertainty (Ben-Haim, 2019). IGT begins with the premise that decisions are based on a set of data, scientific theories, empirical relations, knowledge, and contextual understanding, referred to as models. If uncertainty can be accurately described by probability distributions that are correct and comprehensive and whose interdependencies are well understood, then there is no need for the IG method. The purpose of IGT is to manage the difference between what is known and what needs to be known to make the correct decision. The first central principle of IGT is to focus on satisficing, achieving what is most important to achieve, rather than optimizing. The second pillar of IGT is to seek actions that are robust, that will achieve the satisficing outcomes under a wide range of contingencies. The IGT process begins with the development of a model that describes the current understanding of the system at issue. Using the model, alternative actions are evaluated with respect to their ability to achieve the satisficing objectives. Next, one considers the possibility that the model may be incorrect and assesses how wrong it could be in all relevant ways. Preferred actions are those that achieve the satisficing objectives under the widest range of plausible deviations from the model, a criterion termed "robust satisficing".

Engineering Options Analysis (EOA)

Engineering Options Analysis, a highly simplified version of which was used to analyze the BEV vs. BEV+FCEV example above, is a narrower concept than the four methods previously discussed. Its goal is the planning, designing and managing of an engineering system under uncertainty (de Neufville and Smet, 2019). EOA is related to the Theory of Real Options Analysis but differs in that it handles deep uncertainty, considers multiple options simultaneously and allows for multiple measures of merit (such as GHG reductions and their cost-effectiveness, as in the simplified example). EOA includes the three fundamental components of all the methods of decision making under deep uncertainty described above:

1. Framing the analysis by,
    - formulating the problem,
    - specifying objectives and
    - developing a model of the system,
2. Performing exploratory uncertainty analysis by,
    - identifying a range of options,
    - identifying uncertainties and generating a range of scenarios
    - estimating the system's performance under the scenarios via computer simulation and
    - analyzing the results to identify short-term actions and long-term adaptations,
3. Implementing adaptively by,
    - choosing an initial action,
    - monitoring systematically,
    - taking adaptive action when indicated.

EOA was used in the BEV vs. BEV + FCEV example in section 3 because it is the most straightforward of the five DMDU methods. However, a real EOA would be far more complex, including more options such as low carbon fuels, and identifying additional uncertainties such as related technologies for grid decarbonization, production of hydrogen from renewable, and hydrogen delivery and dispensing.

Common elements of the five methods

All five methods for developing policies and plans under deep uncertainty contain the following five principles:

- Explicit consideration of uncertainties
- Explicit consideration of alternative courses of action and their vulnerabilities
- An emphasis on robustness, achieving the objectives under a wide range of contingencies, rather than optimality
- Continuous monitoring of successes, failures, threats and opportunities
- Planning to adapt, expecting to change policies and plans as indicated by future developments

Although the methods systematize learning from experience and increasing knowledge differently, all include monitoring, re-analysis and adaptation as critical to coping with deep uncertainty.

How do Climate Plans Measure Up?

So far, it appears that none of the formal methods for decision making under deep uncertainty has been applied to the problem of formulating DD policies in the U.S. Yet the five principles shared by the formal methods have all been applied to a greater or lesser degree. This section subjectively compares four transportation decarbonization plans with respect to their strategies for dealing with the four categories of uncertainty. The comparison is not an overall evaluation of the quality of the decarbonization plans or the likelihood they will succeed. It is concerned only with the plans' management of uncertainties. Furthermore, there is as yet no objective or quantitative method for evaluating the goodness of DD policies with respect to uncertainty. The ratings that follow are subjective and primarily intended to illustrate the extent to which policy strategies explicitly address the types of uncertainty identified in Table 1. The subjective ratings of the four plans are summarized in table 3.

U.S. Mid-Century Strategy of 2016

The U.S. Mid-Century Strategy (MCS) was developed to extend the goal of a 17 percent reduction in GHG emissions by 2020 set by the Climate Action Plan (EOP, 2013) to achieve an economy-side reduction in GHG emissions of 80 percent by 2050 (White House, 2016). The MCS presents six scenarios for GHG reduction by 2050, all of which meet the 80 percent reduction goal. The MCS report states that the scenarios were developed drawing on a robust literature, informed by consultations with stakeholders, in collaboration with other nations and supported by original analysis and modeling. Acknowledging a limited ability to represent uncertainties, the MCS instead aimed at "…providing a basis for understanding the key opportunities and challenges related to achieving the MCS vision." (White House, 2016, p. 30). The six scenarios were: 1) a Benchmark case with all key technologies and policies available, 2) a case without CO2 removal technologies, 3) one with limited availability CO2 sinks, 4) a case without carbon capture, utilization and storage, 5) smart growth and 6) a case with limited biomass production.

1. The general areas of public policy identified as critical to accomplishing the transition to deep decarbonization are:
2. Economy-wide emissions pricing
3. Increased public and private support for research, development, demonstration and deployment
4. Efficiency standards for appliances, vehicles and buildings
5. Support for infrastructure
6. Incentives for negative emissions technologies.

No specific policies or measures to build consensus or public support for DD policies are provided. Details describing the strength of the policies and specifics concerning implementation are not provided, although sector-specific discussions mention tax incentives, emissions regulations and provide some discussion of the need for policies beyond pricing carbon to overcome transition barriers. The transportation section discusses promoting EVs and, to a lesser extent FCEVs, biomass fuels and reducing vehicle travel. Technologies for non-highway modes are identified but policies to promote their adoption are not. The MCS notes out the need to support those who may be harmed in the short run by the economy-wide transition. Again, specific actions are not identified. The strategy calls out the necessity of allowing time for the economy to adjust and additional support, including workforce training and development, especially for low-income and households that are reliant on the high-carbon economy. The need for strong international cooperation is recognized, presumably to be achieved through international agreements such as the Paris Agreement of 2015.

Clean Futures Act (proposed)

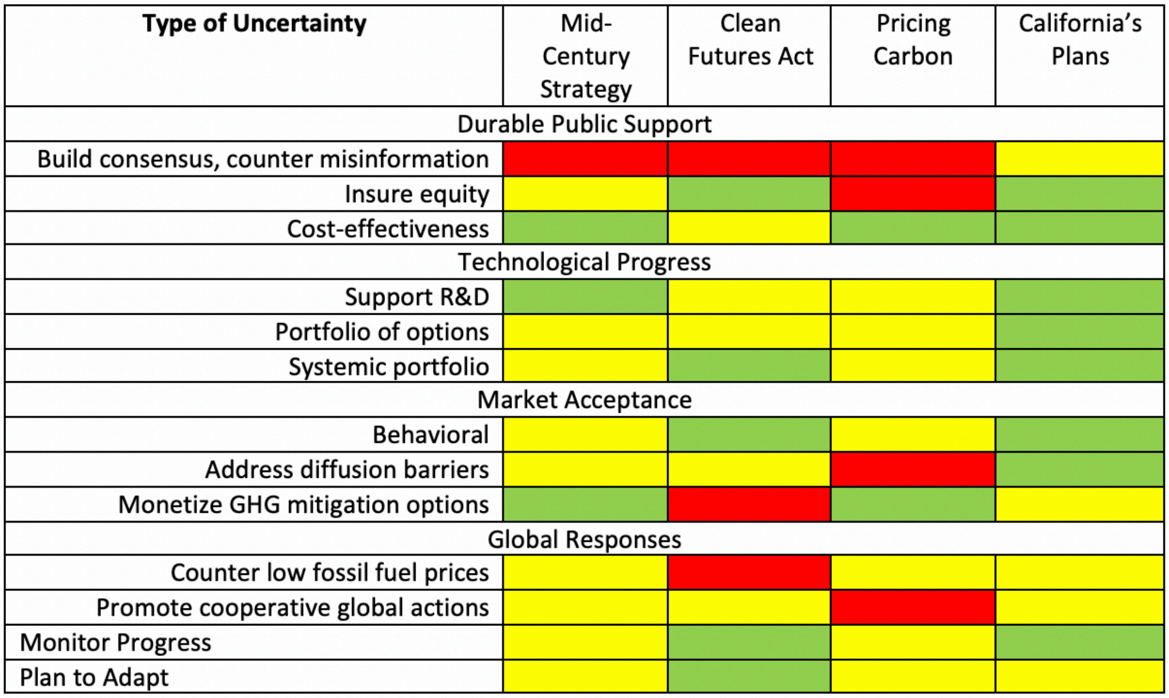
The Clean Futures Act (HR, 2020) is a Bill proposed in the U.S. House of Representatives that sets an ambitious goal of making the U.S. economy “100% clean by 2050”. It addresses all sectors and sources of GHG emissions and makes equity integral to the plan to reduce GHG emissions. It requires federal agencies and states to develop, monitor, frequently re-evaluate and adapt climate plans. It requires the EPA to set GHG emission standards under the Clean Air Act for all transportation modes and promotes BEVs and charging infrastructure. However, it offers far less support for fuel cell vehicles and hydrogen refueling infrastructure.[14] Although it is likely that the standards set by rule will be cost-effective, there is no specific requirement for cost-effectiveness despite the fact that minimum rates of improvement are set by the Act. Government agencies are directed to consider incentives as a means of promoting GHG mitigation but there are no specific provisions for vehicle subsidies or mechanisms for funding such incentives. A key missing element is a mechanism, such as a carbon tax or cap-and-trade system, that would allow the energy industry to monetize investments in low-C

---

[14] The plan offers a subsidy for hydrogen refueling stations of up to $75,000, the same subsidy offered to DC fast charging stations (DCFC). This is actually very unequal treatment since fuel cell vehicles will require many fewer refueling stations than BEVs will require chargers and the cost of a hydrogen refueling stations is more than ten times the cost of a DCFC.

fuels and infrastructure and potentially offset the possibility of very inexpensive fossil fuels as the world decarbonizes.

Table 3. How well do decarbonization strategies address uncertainty: A comparison of four plans.



Type of Uncertainty	Mid-Century Strategy	Clean Futures Act	Pricing Carbon	California's Plans
Durable Public Support				
Build consensus, counter misinformation	🟥	🟥	🟥	🟨
Insure equity	🟨	🟩	🟥	🟩
Cost-effectiveness	🟩	🟨	🟩	🟩
Technological Progress				
Support R&D	🟩	🟨	🟨	🟩
Portfolio of options	🟨	🟨	🟨	🟩
Systemic portfolio	🟨	🟩	🟨	🟩
Market Acceptance				
Behavioral	🟨	🟩	🟨	🟩
Address diffusion barriers	🟨	🟨	🟥	🟩
Monetize GHG mitigation options	🟩	🟥	🟩	🟨
Global Responses				
Counter low fossil fuel prices	🟨	🟥	🟨	🟨
Promote cooperative global actions	🟨	🟨	🟥	🟨
Monitor Progress	🟨	🟩	🟨	🟩
Plan to Adapt	🟨	🟩	🟨	🟨

(Green = specific and systematic; Yellow = partial or indirect ; Red = largely or entirely absent)

Pricing Carbon

Although there is no specific plan that proposes pricing carbon as the only strategy to achieve DD, it is frequently asserted to be the optimal and sometimes the only necessary policy for mitigating GHG emissions, especially by economists who consider regulatory policies to be inefficient (e.g., Rabe, 2018; Economists, 2019). Pricing carbon creates an economic incentive to reduce GHG emissions that will have wide-ranging effects across the economy. Moreover, carbon pricing would incentivize reducing carbon emissions to some degree under any conceivable future conditions. However, it does not directly address most of the sources of uncertainty identified in Table 1. Sustained public support is a particularly difficult challenge but one that might be addressed by redistributing revenues (e.g., CLC, 2020; Carattini et al., 2018). On the other hand, pricing carbon can be a particularly effective means of addressing the problem of countering low fuel prices, a weak point for other plans.

California's Climate Policies for Transportation

Although there are clearly limitations on what a state can do versus a nation, California has one of the world's largest economies and in the U.S. has taken a unique position of leadership in addressing the problem of DD. The cursory assessment here is based on existing policies rather than prospective analyses such as (E+EE, 2020). On the other hand, California's state and local governments have adopted a broad range of policies, not all of which are considered here.

Transportation is the largest source of GHG emissions in California, with 90% of transportation's emissions coming from on-road sources. California has implemented a wide-ranging portfolio of policies to reduce transportation's GHG emissions. Its regulations require reduced vehicle emissions while other policies support R&D, subsidize clean vehicle and clean refueling infrastructure, require sales of ZEV technologies, require reductions in the carbon content of fuels and address demand for travel and its efficiency. Regulatory policies such as ZEV, GHG emissions standards for vehicles and the Low Carbon Fuels Standard, are performance based standards that include tradable credits to enhance their economic efficiency. This approach has been criticized for potential inefficiencies that may result from the interactions of these policies (e.g., Taylor, 2018). However, in terms of dealing with uncertainty California's approach is far more robust than relying on a single approach, such as only pricing carbon. California has some policies specifically designed to address equity concerns, such a "Clean Cars 4 All, and fuel economy/GHG regulations have been shown to have progressive income impacts (Greene and Welch, 2018). However, California has recognized that making DD policies inherently equitable is a larger task and is working to incorporate equity across its policy strategy (e.g., CARB, 2020), for example by recycling carbon cap-and-trade revenues via investments in disadvantaged communities (CCI, 2020).

What Can We Do About Uncertainty?

Uncertainty cannot be eliminated but it can be managed to increase the likelihood of successful DD. First, decision makers can employ planning methods that explicitly take account of uncertainty about the future. Which method is chosen is less important that insuring that all five common elements are included:

- Explicitly considering uncertainties
- Formulating alternative strategies
- Emphasizing robustness over optimality
- Monitoring of progress and threats
- Expecting and planning for adaptation

All four plans assessed above include some aspects of the five elements. None appears to have methodically considered all five.

- Second, DD strategies should address all four categories of uncertainty:
- Uncertainty of public support for DD
- Technological uncertainty
- Market uncertainty
- Global response uncertainty

Of the four categories, the four plans pay too little attention to what is almost certainly the most important: building and sustaining public support for the goal of DD. Building and maintaining public support not only requires informing the public of the facts but countering misinformation, defending trustworthy scientific institutions, and fostering an expectation of government integrity and competence. Public support also depends on convincing the pubic that pathways to DD exist and that the policies to achieve them will be both effective and equitable. This requires making equity integral to DD and not an afterthought.

Technological uncertainty is recognized by all of the plans but only California appears to have analyzed the value of a diverse portfolio of strategies and implemented a range of policies accordingly. With respect to market acceptance, the plans include incentives to promote the adoption of DD technologies and create supporting infrastructure but scarcely acknowledge the importance of overcoming consumers' resistance to novel products and including efforts to address the social and experiential nature of the diffusion process. Finally, except for carbon pricing, none of the plans explicitly acknowledges the likelihood that DD will greatly reduce the prices of fossil fuels, creating an incentive to increase consumption and making DD policies appear to be less cost-effective than they actually are in comparison to an appropriate, business as usual counterfactual.

Deep decarbonization of transportation requires a profound transformation of "… large and deeply entrenched socio-technical systems made up of interconnected technologies, infrastructures, regulations, business models and lifestyles." (Rosenbloom et al., 2020, p. 8665). Accomplishing DD of transportation will take decades and require sustained public support for transformation policies. Uncertainty is inherent and unavoidable. How DD policy prepares for and adapts to uncertain future developments will play a decisive role in the success or failure of DD policies.

References

Alternative Fuels Data Center (AFDC), 2020a. “U.S. HEV Sales by Model”, U.S. Department of Energy, accessed on 8/26/2020 at https://afdc.energy.gov/data/10301 .

Alternative Fuels Data Center (AFDC), 2020b. U.S. PEV Sales by Model”, U.S. Department of Energy, accessed on 9/4/2020 at https://afdc.energy.gov/data/10567 .

Alternative Fuels Data Center (AFDC), 2020c. “Electric Vehicle Charging Station Locations”, U.S. Department of Energy, accessed on 9/4/2020 at https://afdc.energy.gov/fuels/electricity_locations.html#/analyze .

Bataille, C., H. Waisman, M. Colombier, L. Segafredo and J. Williams, 2016. “The Deep Decarbonization Pathways Project (DDPP): insights and emerging issues”, Climate Policy, 16(S1): S1-S6.

Ben-Haim, Y., 2019. “Info-Gap Decision Theory”, Ch. 5 in Marchau et al., eds., Decision Making Under Uncertainty, Springer Nature, Switzerland.

Bento, A., K. Roth, Y. Zuo, 2018. “Vehicle Lifetime and Scrappage Behavior:Trends in the U.S. Used Car Market”, The Energy Journal, 39(1): 159-183.

Bergquist, P. , M. Mildenberger and L. Stokes, 2020. “Combining climate, economic, and social policy builds public support for climate action in the US”, Environmental Research Letters, 15(5): 054019, available at https://iopscience.iop.org/article/10.1088/1748-9326/ab81c1/pdf .

Bloomberg New Energy Futures (BNEF), 2020. “A Behind the Scenes Take on Lithium-ion Battery Prices”, accessed at https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/ and “Battery Pack Prices Fall As Market Ramps Up With

Market Average At $156/kWh In 2019", accessed at https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/ on 8/26/2020.

bp, 2020. "bp's carbon pricing principles", accessed on 9/11/2020 at https://www.bp.com/en/global/corporate/sustainability/climate-change/our-role-in-the-energy-transition/our-carbon-pricing-principles.html .

Brandão, L., J. Dyer and W. Hahn, 2005. "Using Binomial Decision Trees to Solve Real-Option Valuation Problems", Decision Analysis, 2(2): 69-88.

Brückmann, G. and T. Bernauer, 2020. "What drives public support for policies to enhance electric vehicle adoption?", Environmental Research Letters, 15: 094002, available at https://iopscience.iop.org/article/10.1088/1748-9326/ab90a5/pdf .

California Air Resources Board (CARB), 2020. "Sustainable Transportation Equity Project (STEP), accessed on 9/11/2020 at https://ww3.arb.ca.gov/msprog/lct/opportunitiesgov/step.htm .

California Climate Investments (CCI), 2020. 2020 Annual Report: Cap and Trade Dollars at Work, accessed on 9/11/2020 at http://www.caclimateinvestments.ca.gov/annual-report .

California Fuel Cell Partnership (CAFCP), 2020. "By the numbers", accessed on 9/4/2020 at https://afdc.energy.gov/stations/#/analyze?country=US&fuel=HY .

California Fuel Cell Partnership (CAFCP), 2020. "By the numbers", accessed on 9/11/2020 at https://cafcp.org/sites/default/files/FCEV-Sales-Tracking.pdf .

Carattini, S., S. Kallbekken and A. Orlov, 2018. "How to win public support for a global carbon tax", Nature 565, pp. 289-291.

Climate Leadership Council (CLC), 2020. "Advantages of a Carbon Dividends Plan", accessed on 9/11/2020 at https://clcouncil.org/advantages-of-a-climate-dividends-plan/ .

Coase, R., 1960. "The Problem of Social Cost", J. Law & Economics, 3:2-44 .

Davis, S., S. Williams and R. Boundy, 2020. Transportation Energy Data Book, Edition 38, Table 2.3, Oak Ridge National Laboratory, accessed on 8/25/2020 at https://tedb.ornl.gov/data/ .

de Neufville, and K. Smet, 2019. "Engineering Options Analysis (EOA)", Ch. 6 in Marchau et al., eds., Decision Making Under Uncertainty, Springer Nature, Switzerland.

Drews, S. and J. van den Bergh, 2016. "What explains public support for climate policies? A review of empirical and experimental studies", Climate Policy, 16(7): 855-876.

Economists, 2019. "Economists' Statement on Carbon Dividends", published in the Wall Street Journal, 1/16/2019, accessed at https://www.econstatement.org/ .

Energy +Environmental Economics (E+EE), 2020. Achieving Carbon Neutrality in California, accessed on 1/12/2020 at https://ww2.arb.ca.gov/sites/default/files/2020-10/e3_cn_final_report_oct2020_0.pdf .

Energy Information Administration (EIA), 2020. Annual Energy Review 2020. Table 2.5, accessed on 9/11/2020 at https://www.eia.gov/totalenergy/data/annual/ .

European Commission (EC), 2020. "Green Deal: Coal and other carbon-intensive regions and the Commission launch the European Just Transition Platform", accessed on 11/18/2020 at https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1201

Executive Office of the President (EOP), 2013. The President's Climate Action Plan, Executive Office of the President, accessed on 9/10/2020 at https://obamawhitehouse.archives.gov/sites/default/files/image/president27sclimateactionplan.pdf .

Federal Reserve Bank of St. Louis (FRED), 2020a. "Light Weight Vehicle Sales: Autos and Light Trucks", accessed on 9/24/2020 at https://fred.stlouisfed.org/series/ALTSALES#0 .

Federal Reserve Bank of St. Louis (FRED), 2020b. "Gross Domestic Product: Implicit Price Deflator", accessed on 8/28/2020 at https://fred.stlouisfed.org/series/GDPDEF# .

Gerarden, T., R. Newell, R. Stavins and R. Stowe, 2015. "An assessment of the energy efficiency gap and its implications for climate change policy", Working Paper 20905, National Bureau of Economic Research, Cambridge, MA.

Gillingham, K. and K. Palmer, 2014. "Bridging the energy efficiency gap: policy insights from economic theory and empirical evidence", Review of Environmental Economics and Policy, 8(1): 18-38.

Gillis, J. and M. Cooper, 2019. "Consumer Attitudes Towards the Rollback and Freeze of Fuel Economy Standards", Consumer Federation of America, accessed on 8/31/2020 at https://consumerfed.org/wp-content/uploads/2019/05/Consumer-Attitudes-Toward-Fuel-Efficiency-Report.pdf

Greene, D., J. Greenwald and R. Ciez, 2020a. "U.S. fuel economy and greenhouse gas standards: What have they achieved and what have we learned?", Energy Policy, https://www.sciencedirect.com/science/article/pii/S0301421520305048 .

Greene, D., C. Sims and M. Muratori, 2020b. "Two trillion gallons: Fuel savings from fuel economy improvements to US light-duty vehicles, 1975–2018", Energy Policy, 142:111517, https://doi.org/10.1016/j.enpol.2020.111517 .

Greene, D., J. Ogden and Z. Lin, 2020c. "Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles", forthcoming, eTransportation.

Greene, D., E. Kontou, B. Borlaug, A. Brooker, M. Muratori, 2020. "Public charging infrastructure for electric vehicles: What is it worth?", Transportation Research D, vol. 78: 102182, https://doi.org/10.1016/j.trd.2019.11.011 .

Greene, D., 2019. "Implications of Behavioral Economics for the Costs and Benefits of Fuel Economy Standards", Current Sustainable/Renewable Energy Reports, 6(4): 177-192.

Greene, D. and J. Welch, 2018. "Impacts of fuel economy improvements on the distribution of income in the US", Energy Policy, vol. 122,. pp. 528-541.

Greene, D., A. Khattak, J. Liu, X. Wang, J. Hopson and R. Goeltz, 2017. "What is the evidence concerning the gap between on-road and Environmental Protection Agency fuel economy ratings?", Transport Policy, 53: 146-160.

Greene D., D. Evans and J. Hiestand, 2013. "Survey evidence on the willingness of U.S. consumers to pay for automotive fuel economy", Energy Policy, 61: 1539-1550.

Greene, D., 2011. "What's Greener than a VMT Tax? The Case for an Indexed Energy User Fee to Finance U.S. Surface Transportation," Transportation Research D-Environment, vol. 16, pp. 451-458.

Griem, P., A. Solomon and C. Beyer, 2020. "Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation", Nature Communications, https://doi.org/10.1038/s41467-020-18402-y .

Haasnoot, M., A. Warren and J. Kwakkel, 2019. "Dynamic Adaptive Policy Pathways (DAPP)", Ch. 4 in Marchau et al., eds., Decision Making Under Uncertainty, Springer Nature, Switzerland.

Hamilton, J.D., 2009. 30(2), "Understanding Crude Oil Prices", The Energy Journal, 179-206.

Heutel, G., 2020. "In defense of alternatives to pollution pricing", Economists for Inclusive Prosperity , accessed on 8/24/2020 at https://econfip.org/wp-content/uploads/2020/05/26.In-Defense-of-Alternatives-to-Pollution-Pricing.pdf .

House Resolution (HR), 2020. The Clean Futures Act: A Bill, accessed on 9/8/2020 at https://energycommerce.house.gov/sites/democrats.energycommerce.house.gov/files/documents/0128%20CLEAN%20Future%20Discussion%20Draft.pdf .

Huber, R., M. Wicki and P. Bernauer, 2020. "Public support for environmental policy depends on beliefs concerning effectiveness, intrusiveness, and fairness", Environmental Politics, 29(4): 649-673.

Hsieh, I-Y., M. Pan, Y-M. Chiang and W. Green, 2019. "Learning only buys you so much: Practical limits on battery price reduction", Applied Energy, 239: 218-224.

IPCC, (2018). Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, accessed on 8/25/2020 at https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf .

International Energy Agency (IEA), 2020. Global EV Outlook 2020, accessed on 9/24/2020 at https://www.iea.org/reports/global-ev-outlook-2020 .

James, B., 2020. "Fuel Cell Systems Analysis", presentation at U.S. Department of Energy, Annual Merit Review Hydrogen and Fuel Cells Program, accessed on 8/28/2020 at https://www.hydrogen.energy.gov/pdfs/review20/fc163_james_2020_o.pdf .

James, B., J. Huya-Kouadio, C. Houchins and D. DeSantis, 2016. "Final Report: Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation

Ph.D. Dissertation, Environmental Engineering, University of Michigan, ORCID iD: 0000-0002-5512-409X .

Jiang, H., 2013. Key Findings on Airplane Economic Life, Boeing, accessed on 8/25/2020 at https://www.boeing.com/assets/pdf/commercial/aircraft_economic_life_whitepaper.pdf .

Just Transition Fund, 2020. National Economic Transition Platform, accessed on 11/18/2020 at https://nationaleconomictransition.org/ .

Lempert, R., 2019. "Robust Decision Making", Ch. 2 in Marchau et al., eds., Decision Making Under Uncertainty, Springer Nature, Switzerland.

Lempert, R., Groves, D., Popper, S., and Bankes, S., 2006. "A general, analytic method for generating robust strategies and narrative scenarios ", Management Science, 52(4), 514–528.

Lutsey, N., 2019. "Update on electric vehicle costs in the United States through 2030", Working Paper 2019-6, International Council on Clean Transportation, accessed on 8/26/2020 at https://theicct.org/publications/update-US-2030-electric-vehicle-cost.

Lempert, R., S. Popper, and S. Bankes, 2003. Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis, MR-1626-RPC, RAND, Santa Monica, California.

Long, Z., J. Axsen and C. Kormos, 2019. "Consumers continue to be confused about electric vehicles: comparing awareness among Canadian new car buyers in 2013and 2017", Environmental Research Letters, 14: 114036

Marchau, V., W. Walker, P. Bloeman and S. Popper, eds., 2019. Decision Making Under Uncertainty, Springer Nature, Switzerland.

Mathy, S., P. Criqui, K. Knoop, M. Fischdick and S. Samadi, 2016. "Uncertainty management and the dynamic adjustment of deep decarbonization pathways", Climate Policy, 16(sup. 1), S47-S62.

McCollum, D., A. Gambhir, J. Rogelj and C. Wilson, 2020. "Energy modelers should explore extremes more systematically in scenarios", Nature Energy, 17 February, https://doi.org/10.1038/s41560-020-0555-3 .

Muratori, M. et al., 2020. "The Rise of Electric Vehicles – 2020 Status and Future Expectations", manuscript in review, National Renewable Energy Laboratory, Golden, CO.

National Research Council (NRC), 2020. Climate Change: Evidence and Causes: Update 2020, National Academies Press, Washington, DC.

National Research Council, 2015. Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles, National Academies Press, Washington, D.C.

Nyqvist, B. and M. Nilsson, 2015. "Rapidly falling battery costs for electric vehicles", Nature Climate Change, 5, 329-332.

Pew Research Center (PRC), 2020. "Two-Thirds of Americans Think Government Should Do More on Climate", accessed on 9/11/2020 at https://www.pewresearch.org/science/2020/06/23/two-thirds-of-americans-think-government-should-do-more-on-climate/ .

Pigou, A., 1920. "Divergences Between Marginal Social Net Product and Marginal Private Net Product", Ch. 9 in The Economics of Welfare, MacMillan and Co., London.

Pye, S., N. Sabio and N. Strachan, 2015. "An integrated systematic analysis of uncertainties in UK energy transition pathways", Energy Policy, 87: 673-684.

Rabe, B., 2018. Can We Price Carbon?, MIT Press, Cambridge, MA.

Reynolds, C., 2019. "Decarbonizing Freight Transport: Mobile Carbon Capture from Heavy-Duty Vehicles", Ph.D. Dissertation, Environmental Engineering, University of Michigan, ORCID iD: 0000-0002-5512-409X .

Rogers, E., 1995. Diffusion of Innovations. Fourth Ed., The Free Press, New York.

Rosenbloom, D., J. Markard, F. Geels and L. Fuenfschilling, 2020. "Why carbon pricing is not sufficient to mitigate climate change – and how "sustainability transition policy" can help", PNAS, 117(16): 8664-8668.

Sharma, S. and F. Maréchal, 2019. "Carbon Dioxide Capture From Internal Combustion Engine Exhaust Using Temperature Swing Adsorption", Frontiers in Energy Research, v. 7. Article 143.

Stone, C., 2015. "The Design and Implementation of Policies to Protect Low-Income Households under a Carbon Tax", Center on Budget and Policy Priorities, accessed on 11/18/2020 at https://www.cbpp.org/sites/default/files/atoms/files/9-21-15climate.pdf .

Taylor, M., 2018. Assessing California's Climate Policies – Transportation, Legislative Analyst's Office, State of California, accessed at https://lao.ca.gov/Publications/Report/3912 on 9/9/2020.

Treen, K., H. Williams and S. O'Neil, 2020. "Online misinformation about climate change", acc WIREs, 11(5): DOI: 10.1002/wcc.665, accessed on 9/14/2020 at https://onlinelibrary.wiley.com/doi/epdf/10.1002/wcc.665 .

U.S. Energy Information Administration (USEIA), 2020a. "Gasoline and Diesel Fuel Update", accessed on 8/27/2020 at https://www.eia.gov/petroleum/gasdiesel/ .

U.S. Energy Information Administration (USEIA), 2020b. International Energy Outlook 2019, Tables A5 and G2, accessed on 8/27/2020 at https://www.eia.gov/outlooks/ieo/ .

U.S. Energy Information Administration (USEIA), 2020c. Annual Energy Outlook 2020, Table 1, accessed on 9/24/2020 at https://www.eia.gov/outlooks/aeo/ .

United States Environmental Protection Agency (USEPA), 2016. "Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission

Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025, EPA-420-D-16-900, July 2016.

Usher, W. and N. Strachan, 2012. "Critical mid-term uncertainties in long-term decarbonization pathways", Energy Policy, 41: 433-444.

Waisman, H. et al., 2019. "A pathway design framework for national low greenhouse gas emission development strategies", Nature Climate Change, 9(April): 261-268.

Walker, W., V. Marchau and J. Kwakkel, 2019. "Dynamic Adaptive Planning (DAP)", Ch. 3 in Marchau et al., eds., Decision Making Under Uncertainty, Springer Nature, Switzerland.

White House, 2016. United States Mid-Century Strategy for Deep Decarbonization, accessed at https://unfccc.int/files/focus/long-term_strategies/application/pdf/mid_century_strategy_report-final_red.pdf on 1/5/2021.

www.fueleconomy.gov, 2020. "Downloadable Fuel Economy Data", U.S. Department of Energy and Environmental Protection Agency, accessed on 8/25/2020 at https://www.fueleconomy.gov/feg/download.shtml .

Yang, Z. and A. Bandivadekar, 2017. "Light-duty Vehicle Greenhouse Gas and Fuel Economy Standards", International Council on Clean Transportation, accessed on 9/24/2020 at https://theicct.org/sites/default/files/publications/2017-Global-LDV-Standards-Update_ICCT-Report_23062017_vF.pdf .